Final Program Report

Harvesting Electric Energy During Walking with a Backpack: Physiological, Ergonomic, Biomechanical, and Electromechanical Materials, Devices, and System Considerations

Award Number: N00014-03-1-0569

Period of Performance

April 1, 2003 – December 31, 2004

Submitted to

Dr. Promode R. Bandyopadhyay

ONR 342
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217

Submitted by

Qiming Zhang
The Pennsylvania State University
Department of Electrical Engineering and Materials Research Institute
University Park, PA 16802
Phone: 814-863-8994 Fax: 814-863-7846 Email: qxz1@psu.edu

Heath Hofmann
Department of Electrical Engineering
The Pennsylvania State University, University Park, PA 16802

January 2005

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01/05/2005	Final Program Report	April 1,2003 to December 31, 2004

4. TITLE AND SUBTITLE

Harvesting Electric Energy During Walking with a Backpack: Physiological, Ergonomic, Biomechanical and Electromechanical Materials, Devices, and System Considerations

5a. CONTRACT NUMBER

N00014 03 1 0569

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Qiming Zhang

Heath Hogmann

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Penn State University Department of Electrical Engineering and Materials Research Institute
187 Materials Research Institute, University Park PA 16802

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Dr. Promode R. Bandyopadhyay
Office of Naval Research Ballston Centre Tower One
800 North quincy Street
Arlington VA 22217

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The objective of this program is to investigate approaches which make use of several classes of electroactive materials developed recently for harvesting electric energy during walking. These newly developed electroactive materials including the electrostrictive PVDF based polymers and piezoelectric relaxor single crystals have shown order of magnitude improvement in terms of the elastic energy density in comparison with the traditional piezoelectric materials and much improved the electromechanical coupling factors. Furthermore, in this program, we show that the electromechanical conversion efficiency of a properly designed energy harvesting system can be much higher than these of the electroactive material itself. Using this principle, we demonstrated that an electric energy output of 39 mJ/cc with a 10% efficiency can be obtained from the electrostrictive PVDF polymers. Using 1-3 composites with ferroelectric relaxor single crystals, harvested electric power density of 96 mW/cc has been obtained (at 4 Hz). The experimental results have revealed several issues related to the energy harvesting systems utilizing electroactive materials such as

15. SUBJECT TERMS

(Cont abstract)
the effect of the dielectric loss to the energy efficiency and the limitation of the commercial power electronic circuit components to the operation voltage of these systems.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Qiming Zhang
UU	UU	UU	UU	15	19b. TELEPHONE NUMBER *(Include area code)* 814-863-8994

Abstract

The objective of this program is to investigate approaches which make use of several classes of electroactive materials developed recently for harvesting electric energy during walking. These newly developed electroactive materials including the electrostrictive PVDF based polymers and piezoelectric relaxor single crystals have shown order of magnitude improvement in terms of the elastic energy density in comparison with the traditional piezoelectric materials and much improved the electromechanical coupling factors, both of which are required for high performance energy harvesting systems. Furthermore, in this program, through a systematically analysis, we have shown that the input mechanical energy density to an electroactive material and the electromechanical conversion efficiency of a properly designed energy harvesting system, i.e., by properly designed electric controlling circuits, can be much higher than these of the electroactive material itself. Using this principle, we demonstrated that an electric energy output of 39 mJ/cc with a 10% efficiency can be obtained from the electrostrictive PVDF polymers. Using 1-3 composites with ferroelectric relaxor single crystals, harvested electric power density of 96 mW/cc has been obtained (at a frequency of 4 Hz). The experimental results have revealed several issues in utilizing these electroactive materials for the electric energy harvesting: (1) The dielectric hysteresis loss at high electric fields for the electrostrictive PVDF polymers should be avoided in order to achieve high efficiency; (2) For the 1-3 composites with the ferroelectric relaxor single crystals, a DC bias field is needed in order to stabilize the material in the piezoelectric state; (3) Because of the limitation of the commercially available power electronic components as well as relatively small electric energy involved in the energy harvesting systems (~ 1 watts or below), it is preferred to operate the energy harvesting system to below 1000 volts in using active control of the energy harvesting system with the commercially available power electronic components.

I. Introduction

The modern warfare is marked by sophisticated electronics used in almost all parts of the weaponry systems which enhance significantly the military capability and reduce the battlefield causality. One of the prices for this increased reliance on the electronics is the increased weight of the batteries. Carrying these batteries can increase the pack weight to upwards of 80 lbs. Our goal in this study is to develop a device that "harvests" some of the mechanical energy during walking and converts it to electrical energy to charge the batteries so that the amount of batteries that must be carried for each day in the field can be reduced significantly. Furthermore, through this investigation, we also intend to establish general guidelines for the energy harvesting using the electroactive materials to achieve the highest possible efficiency and maximum possible electric power output.

In a typical energy harvesting process, an electroactive material absorbs the external mechanical energy, and through a proper electromechanical conversion process to convert that energy into electric form. Finally, this converted electric power, through a power electronic interface, is delivered to the load. Therefore, several steps must be

taken in designing an energy harvesting system to effectively convert the mechanical power available in an external medium into the electric power used by an electric load: (i) mechanical impedance match of the electroactive material system to the environment to realize maximum mechanical energy transfer into the electroactive material system; (ii) high electromechanical conversion efficiency of the electroactive material system; (iii) a proper power electronics to transfer most effectively converted electric power into the electric load. Furthermore, we use the electroactive material system which couples the electroactive material with a properly designed electronics to "smartly" tune the material parameters during the energy harvesting cycle for the energy harvesting system. These electronic additions can improve the electromechanical conversion efficiency and/or the mechanical impedance match to the external mechanical environment. That is, through properly designed power electronic circuit, the energy conversion efficiency of an electroactive material system can be much higher than that of the electroactive material.

II. Results

(i) Optimizing the energy harvesting cycle to achieve higher electric energy output and efficiency.[1] Although the electromechanical conversion efficiency for a given electroactive material is a fixed value, for energy harvesting from a given mechanical environment, the amount of mechanical energy as well as the system efficiency can be improved markedly by optimizing the electric boundary conditions during the energy harvesting cycle. For example, presented in Table I is a comparison of the maximum electric energy density harvested W_{1max} and system effective coupling factor k for a given electroactive polymer (electrostrictive PVDF) under a maximum 150 MV/m field and 20 MPa stress. Apparently, the electric power output depends crucial on the operation conditions of the electronic controlling circuits and can vary over a large range.

Table I.

Electrical Boundary Conditions	W_{1Max}(J/cc)	k
Cycle 1 - Constant field and open-circuit	0.14	0.523
Cycle 2 - Constant field	0.99	0.815
Cycle 3 - Open circuit	0.826	0.834
Cycle 4 - Passive diode circuit	0.082	0.392

Taking electroactive polymers as an example. For mechanical-to-electrical energy harvesting, one can apply various electrical boundary conditions during the stress variation cycle to break the symmetry of stretching and contracting of the electrostrictive polymer, and thereby harvest energy. In order to maximize the harvesting energy density, the boundary conditions have to be designed so that the area enclosed in the loop (see figure 1) is as large as possible without exceeding the limitations of the polymer material (e.g., maximum stress, breakdown field).

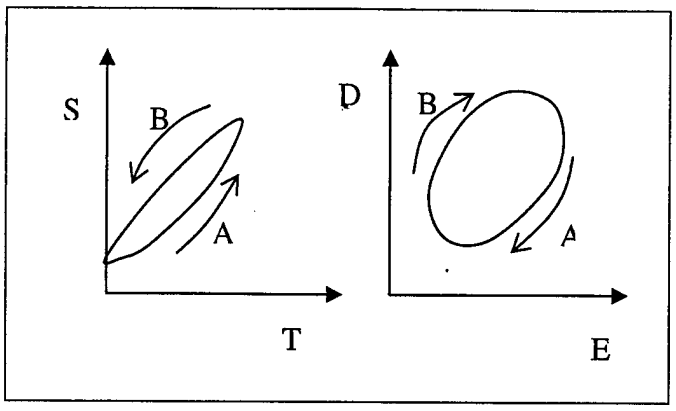


Figure 1. Energy harvesting cycle where the electric energy harvested is the area enclosed by the strain-stress (S-T) or charge density-field (D-E) loop (the two are the same)

Ideally the energy harvesting cycle should consist of the largest loop possible, bounded only by the limitations of the material. However, actual implementation of the optimal energy harvesting cycle in an energy harvesting device may be difficult to achieve. The 4 different energy harvesting cycles listed in Table I correspond to the electrical boundary conditions that can be applied to the device fairly easily with power electronic circuitry. The following is a summary of the analysis for these four cycles using an electrostrictive material under a DC bias field. The results can be easily extended to the piezoelectric material.

Electrostriction is generally defined as quadratic coupling between strain and electrical field. The strain S_{ij} and the electric flux density D_m are expressed as independent variables of the electric field intensity E_n and the stress T_{ij} by the constitutive relation as:

$$\begin{aligned} S_{ij} &= s^E_{ijkl} T_{ij} + M_{mnij} E_n E_m, \\ D_m &= \varepsilon_{mn} E_n + 2M_{mnij} E_n T_{ij}, \end{aligned} \tag{1}$$

Where s^E_{ijkl} is the elastic compliance, M_{nmij} is known as the electric-field-related electrostriction coefficient, and ε_{mn} is the linear dielectric permittivity. An isotropic electrostrictive polymer film contracts along the thickness direction and expands along the film direction when an electric field is applied across the thickness. Assuming the only non-zero stress is applied along x_1, the constitutive relation is then simplified as:

$$\begin{aligned} S &= sT + ME^2 \\ D &= \varepsilon E + 2MET \end{aligned} \tag{2}$$

where

$$E = E_3, D = D_3, S = S_1,$$
$$T = T_1, s = s_{11}, M = M_{31},$$
$$\varepsilon = \varepsilon_{33}$$

The electromechanical coupling factor is defined as:

$$k = \sqrt{\frac{W_1}{W_1 + W_2}},$$

where $W_1 + W_2$ is the input mechanical energy density, and W_1 is the output electrical energy density. The coupling factor is often associated with a specific set of electrical boundary conditions, as will be discussed in the following. In all the discussions, the application of stress cycle starts from zero to a maximum value T_{Max}, and then returns to zero.

- *Energy harvesting cycle #1 – Constant field and open-circuit electrical boundary conditions*

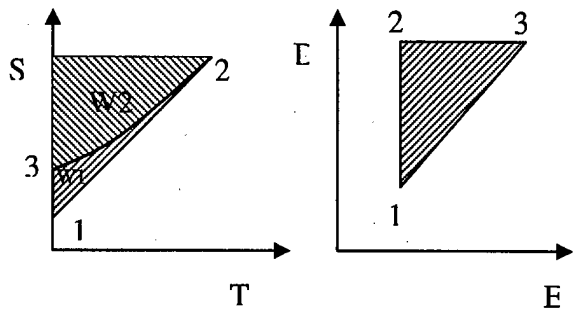


Figure 2. Energy Harvesting Cycle under Constant Field (1-2) and Open Circuit (2-3) Electrical Boundary Conditions

In this cycle, The material is stress free at state 1 of the cycle, and an electric field E_0 is applied and kept constant as the stress is increased to T_{max}, ending in state 2. The electrostrictive device is then open-circuited when the stress is removed, ending in state 3. From state 3 the electric field E_0 is re-established in the material, returning to the original state 1. The total mechanical input energy density available for the energy harvesting for such a cycle can be shown to be $W_1 + W_2 = \frac{1}{2} s T_{max}^2$, while the energy W_1 can be calculated as follows.

As the material is in open-circuit condition from state 2 to 3, the electric flux density is constant and is given by

$$D = \varepsilon E_0 + 2ME_0T_{\max} \tag{3}$$

The electric field-intensity as the stress is removed is therefore given by:

$$E = E_0 \frac{\varepsilon + 2MT_{\max}}{\varepsilon + 2MT} \tag{4}$$

This field-intensity reaches its peak value E_p when the applied stress becomes zero, or

$$E_p = E_0\left(1+\frac{2MT_{\max}}{\varepsilon}\right) = E_0(1+\gamma), \tag{4}$$

Where γ corresponds to the relative change in dielectric constant due to applied stress, and is defined as follows.

$$\gamma = \frac{2MT_{\max}}{\varepsilon} \tag{5}$$

For existing electrostrictive materials, γ is less than 1. Now:

$$\begin{aligned} W_2 &= -\int_2^3 TdS = \frac{1}{2}sT_{\max}^2 - 2\frac{E_0^2}{\varepsilon}M^2T_{\max}^2 \\ &= \frac{1}{2}\left(sT_{\max}^2 - \varepsilon\gamma^2E_0^2\right) \end{aligned} \tag{6}$$

$$\Rightarrow W_1 = 2\frac{E_0^2}{\varepsilon}M^2T_{\max}^2 \tag{7}$$

The coupling factor is therefore given by

$$k = \frac{2ME_0}{\sqrt{s\varepsilon}} \tag{8}$$

The electromechanical coupling factor k for this cycle is that used in the literature as the coupling factor for the material (except that E_0 in here is the lowest field during the cycle). If E_0 is chosen so that the peak electric field intensity E_p is the maximum allowable due to material constraints $E_{\max}$, the maximum harvesting energy density is given by

$$W_{1\max} = \frac{\gamma}{(1+\gamma)^2}MT_{\max}E_{\max}^2 \tag{9}$$

And the coupling factor associated with this energy density is given by

$$k = \frac{2ME_{max}}{(1+\gamma)\sqrt{\varepsilon s}} \qquad (10)$$

- *Energy harvesting cycle #2 – Constant-field boundary conditions during stressing and unstressing of material*

Another possible method of imposing electrical boundary conditions is to keep the electric field constant as the material is stressed, change the field to a different constant value, and then remove the stress. Such a cycle is shown in Figure 3.

A constant electric field E_0 is applied from state 1 to state 2 as the stress is increased to T_{max}. From state 2 to state 3 the electric field is increased from E_0 to E_1, and then kept constant as till the stress is reduce from T_{max} to 0 from state 3 to state 4. Finally, at zero stress the electric field is reduced to E_0, returning to state 1. In the mechanical stress/strain plot the path 1-4 and 2-3 are not parallel, which is due to the stress dependence of dielectric constant. The converted energy can be shown to be

$$W_1 = T_{max} M\left(E_1^2 - E_0^2\right) \qquad (11)$$

The input energy density $W_2 = \frac{1}{2} s T_{max}^2$, and the coupling factor is therefore given by

$$k = \sqrt{\frac{M\left(E_1^2 - E_0^2\right)}{\frac{1}{2} s T_{max} + M\left(E_1^2 - E_0^2\right)}} \qquad (12)$$

The maximum energy harvesting density and coupling occurs when E_0 is set to be zero and E_1 is set to E_{max}.

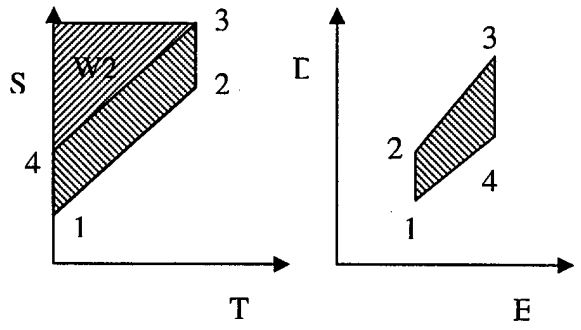


Figure 3. Energy Harvesting Cycle Under Constant Electrical Field Conditions as the Material is Stressed and Unstressed

- *Energy harvesting cycle #3 – Open-circuit boundary conditions during stressing and unstressing of material*

Another type of electrical boundary condition is to have open-circuit boundary

conditions as the stress is applied and removed, as shown in Figure 4. From state 1 to state 2 and state 3 to state 4, the electric field changes automatically as the stress changes. From state 2 to state 3 and from state 4 to state 1, the electric field is changed through the electrical interface. We define the field at state 1 to be E_0 and the field at state 3 to be E_4.

And the energy harvesting density is

$$W_1 = \frac{MT_{\max}}{1+\gamma}[E_4^2 - E_0^2] \tag{13}$$

Its associated coupling factor is given by

$$k = \sqrt{\frac{(1+\gamma)M[E_4^2 - E_0^2]}{\frac{1}{2}(1+\gamma)^2 sT_{\max} + (1+\gamma)M[E_4^2 - E_0^2] - 2M^2 T_{\max} E_4^2 / \varepsilon}} \tag{14}$$

The maximum harvesting density then occurs then $E_0 = 0$ and $E_4 = E_{\max}$.

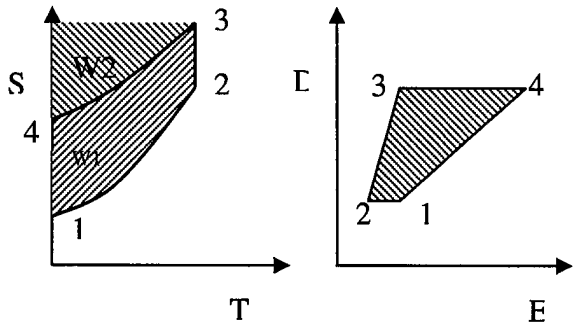


Figure 4. Energy Harvesting Cycle Under Open-Circuit Conditions as Stress is Applied and Removed

- *Energy Harvesting Cycle #4 - Passive diode circuit for energy harvesting*

A circuit that has been proposed for electrostatic-based energy harvesting can also be used with electrostrictive materials, and is shown in Figure 5. The circuit uses high voltage diodes for passive switching. The main advantage of this circuit design is simplicity (This is the circuit used in the SRI International energy harvesting experiment). [2]

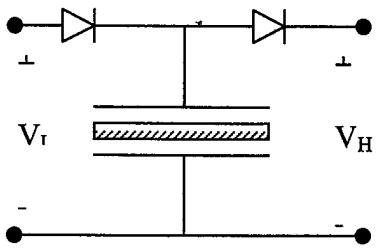


Figure 5. Passive Diode Circuit for Energy Harvesting

The energy harvesting cycle is shown in 6. However, as the circuit is passive, the voltage change across the device occurs only due to the electrostrictive effect. As a result, it can be shown that the voltages V_L and V_H are constrained by the following condition:

$$V_L < V_H < \gamma V_L \tag{15}$$

These constraints severely impair the energy harvesting density and coupling factor when γ is small.

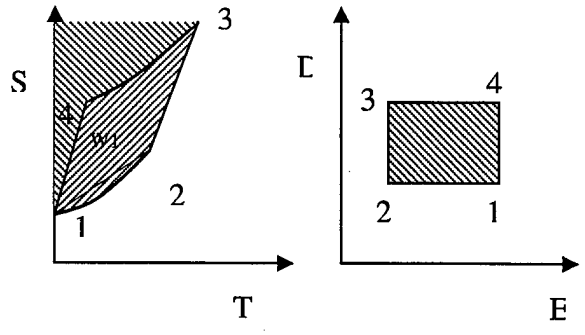


Figure 6. Energy Harvesting Cycle for Passive Diode Circuit

The energy conversation density and coupling is maximized when

$$E_L = \frac{2+\gamma}{2(1+\gamma)} E_H \tag{16}$$

If we set $E_H = E_{\max}$, the maximum energy harvesting density is given by

$$W_{1\max} = \frac{\gamma}{2(1+\gamma)} M T_{\max} E_{\max}^2 \tag{17}$$

And it associated coupling factor is

$$k = \sqrt{\frac{\gamma M E_{\max}^2}{(1+\gamma) s T_{\max} + M E_{\max}^2 \frac{\gamma}{2(1+\gamma)}}} \tag{18}$$

As can be seen from Table I, the passive diode circuit does not provide high energy density output and efficiency. In an early SRI experiment, it was claimed that a high output electric energy density was harvested. The result is not correct and the error is due to the fact that they have reported the discharge electric energy to V_H and have not included the energy input from V_1 to charge the electroactive polymer which is very significant.

(ii) Experimental results of electric energy harvested using the electrostrctive PVDF polymer. As shown in Table I, one of the energy harvesting cycle which can lead to a high energy density and efficiency is the cycle 3. In this energy harvesting cycle, a constant DC electric field is applied when the material is stress and unstressed. Because of the limitation of the power electronics, the operation voltage of the energy harvesting system is preferred to be below 1000 volts. For the electrostrictive PVDF polymers which require an operation field up to 100 MV/m, 1000 volts limit will require the thickness of each electrostrictive polymer film to at 10 μm and a multilayer approach needs to be taken for the device. Because of the earlier termination of the program, we were not able to develop a power electronic circuit as well as the multilayer device with each layer thickness at 10 μm and to perform the experiment. To quickly demonstrate the concept of utilizing smart electronics to tune the electroactive material parameters during the energy harvesting cycle to achieve higher efficiency and higher input mechanical energy density, we approximated such an electric condition with a sinusoidal electric signal (which eliminates the limitation of the power electronics). Detailed analysis indicates that when the AC stress signal and AC electric signal are out of phase by 90°, the system reaches highest energy density harvested. The experimental results with electrostrictive PVDF confirmed this prediction. As shown in Table II, an energy density of 40 mJ/cm^3 can be achieved with the electrostrictive PVDF polymer (corresponding to a coupling factor k=0.31). In the experiment, the maximum electric field is 67 MV/m (much lower than 150 MV/m used in the calculation of Table I, which explains why a lowered energy density and efficiency obtained here compared with that predicted in Table I). This lower field is due to the limitation of the electric breakdown of the test specimen as well as the increase dielectric loss at higher fields. Even with these limitations, the electric energy density and efficiency are already much higher than all the previously reported values (although SRI claimed to have higher energy density,[2] their value is not that from the whole stress loop and therefore, is not the true energy density harvested. This has been analyzed in detail in (i))[1].

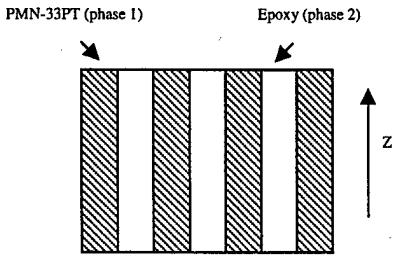
Table II

Material	Efficiencies	Specific energy (mJ/cc)
PVDF*	0.5	0.044
PZT*	1.5~5	2.1
Electrostrictive PVDF polymer	10	39.4

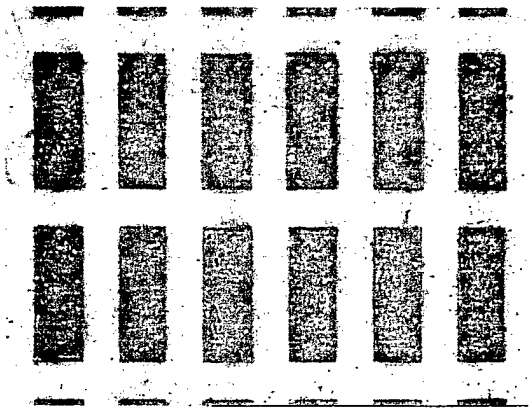
*MIT, IEEE conference on wearable computing 1998

(iii) **Development of 1-3 single crystal-polymer composites with high electromechanical conversion efficiency.**

In our proposal, two classes of electroactive materials were proposed for use for the energy harvesting: the electrostrictive PVDF polymer and 1-3 piezocomposite using the high efficiency piezoelectric single crystals. In this program, the fabrication process of 1-3 single crystal (PMN-PT)-polymer composite was investigated in order to achieve high coupling factor. Single crystals of 0.67PMN-0.33PT oriented along <001> direction were used in the investigation because of the high coupling factor (>0.9). The single crystals were poled at room temperature under a field of 10 kV/cm. In the 1-3 composite fabrication process, extra-precaution has to be taken in order not to cause damage to the single crystals. The poled single crystals of 1 mm thick (<001> oriented) were first cut along the <100> direction using the Automatic Dicing Saw with the a curf width of 100 μm. The cutting process was followed by filling of Mereco 1650 series epoxy to form a 2-2 composite. The 2-2 composites were cut in perpendicular direction and then filled with the epoxy to form the final 1-3 composites (see figure 7). The 1-3 composites were polished to a thickness of about 0.7 mm (see figure 7(a), thickness along the z-direction) and sputtered Au films of 20 nm thick were used as the electrodes. The composites were poled along the thickness direction in silicon oil for 5 min under a DC field of 1 kV/cm. Several 1-3 composites with piezoelectric single crystal PMN-PT were fabricated and characterized. Shown in figure 7(b) is a top view of a 1-3 single crystal-polymer composite fabricated, where the dark areas are single crystals and the less dark areas are epoxy.



(a)



(b)

Figure 7.

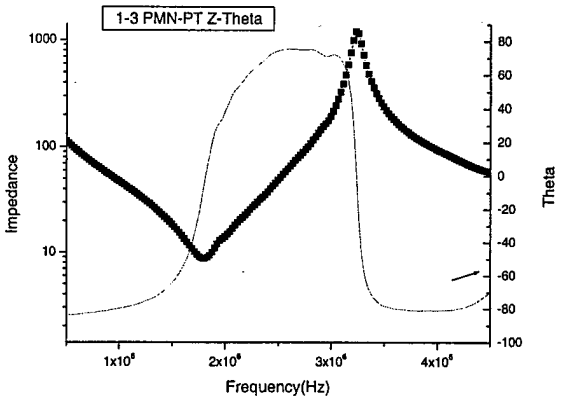


Figure 8. Electric impedance curve for a 1-3 single crystal-polymer composite where the solid curve is the phase angle and the curve with dots is the absolute value of electric impedance

High electromechanical coupling factor was achieved in these composites. Shown in figure 8 is the electric impedance curve for a 1-3 single crystal-polymer composite. The thickness coupling factor k_t of 1-3 single crystal-polymer composite deduced from the data is 0.85. Figure 9 shows how k_t varies with the volume content of the single crystal in the 1-3 composites. In the volume content from 0.4 to 0.6 range, k_t=0.85. In comparison, 1-3 composites with piezoceramics PZT show a coupling factor of 0.59. This difference is significant since the energy conversion efficiency is proportional to the square of the coupling factor (72% for single crystal composites vs. 35% for PZT composites). Moreover, as has been shown in the results from (i), this difference in the coupling factor can also affect the input mechanical energy density in the energy harvesting cycle using external electric boundary condition to maximize the energy output.

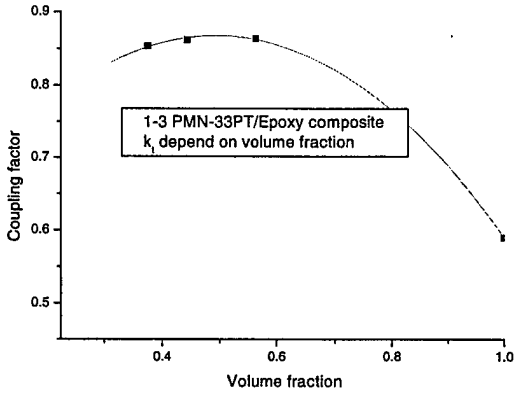


Figure 9. Dependence of kt on the volume fraction of the single crystal in the 1-3 composite

(iv) **Experimental investigation on materials and electric boundary conditions to achieve high energy density harvested with high efficiency.** As a first step, we compared the energy density harvested using 1-3 composites with piezoceramic vs. 1-3 composites with piezo-single crystal. Shown in figure 10 is the schematic of the experiment set-up where the value of the load resistor R_L is determined by the electric impedance matching condition to the electroactive polymer to reach the highest energy density harvested in this configuration. It should be noted

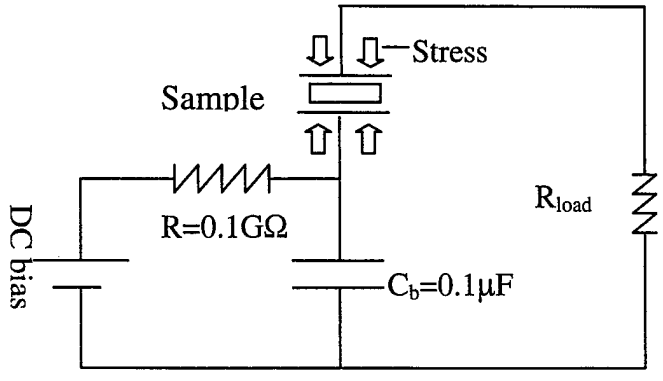


Figure 10. Schematic of the test set-up where the mechanical stress is provided and regulated by an Instron Universal Test Machine

that the efficiency and energy output of this simple circuit are lower than these listed in Table I (as discussed in (i)).

In the following, we derive the efficiency and load condition for the set-up in figure 10. Suppose the stress, strain, and electrical displacement are non-zero only along the z-direction (see figure 7), the constitutive relations of the electroactive material are in the form of

$$\begin{aligned} S &= sT + dE \\ D &= dT + \varepsilon E \end{aligned} \tag{19}$$

where S and T are the strain and stress component, and D and E are the electric displacement and electric field, respectively. s, d, and ε are the elastic compliance, the piezoelectric constant, and the dielectric permittivity. For the 1-3 PMN-33PT/Epoxy composite, Eq (19) can be rewritten as:

$$\begin{aligned} l &= \hat{s}F + \hat{d}V, \\ Q &= \hat{d}F + CV \end{aligned} \tag{20}$$

where the dimensional change l is related to the strain S as l=St, the force F=TA, the charge Q=DA, the voltage V=Et. The spring constant $\hat{s} = s\frac{t}{A}$, the capacitance $C = \varepsilon\frac{A}{t}$ and $d = \hat{d}$. A is the cross section area and t is thickness of the sample.

When a sinusoidal mechanical force $F = F_0 \sin(\omega t)$ is applied on the sample and a sinusoid voltage would be generated, the phase of which is to be determined: $V = V_0 \sin(\omega t + \theta)$, then the charge and current are:

$$\begin{aligned} Q &= \hat{d}F_0 \sin(\omega t) + CV_0 \sin(\omega t + \theta) \\ i &= \frac{\partial Q}{\partial t} = \hat{d}F_0\omega\cos(\omega t) + CV_0\omega\cos(\omega t + \theta) \end{aligned} \tag{21}$$

Finally, after some calculation, the power dissipation of (or delivered to) the resistor is

$$Power = \frac{V_0^2}{2R} = \frac{\omega^2\hat{d}^2F_0^2R}{2(1+\omega^2C^2R^2)} \tag{22}$$

When the dissipation resistor is equal with the impedance of the sample voltage source, the power is the maximum power dissipated in the resistor, so the power peak is at

$$R = \frac{1}{\omega C} \tag{23}$$

At such a resistive load, the output power density is

$$Power_{peak} = \frac{\omega\hat{d}^2F_0^2}{4C} \tag{24}$$

Since the input peak mechanical energy is $2F_0^2\hat{s}$ and the converted electrical for one cycle is $\frac{\pi\hat{d}^2F_0^2}{2C}$. The ratio of two can be related to the electromechanical coupling factor k:

$$\frac{\pi d^2 F_0^2 / 2C}{2F_0^2 \hat{s}} = \frac{\pi d^2}{4C\hat{s}} = \frac{\pi k^2}{4}$$

Shown in figure 11 are the experimental data for the 1-3 composites with piezoceramic PZT.

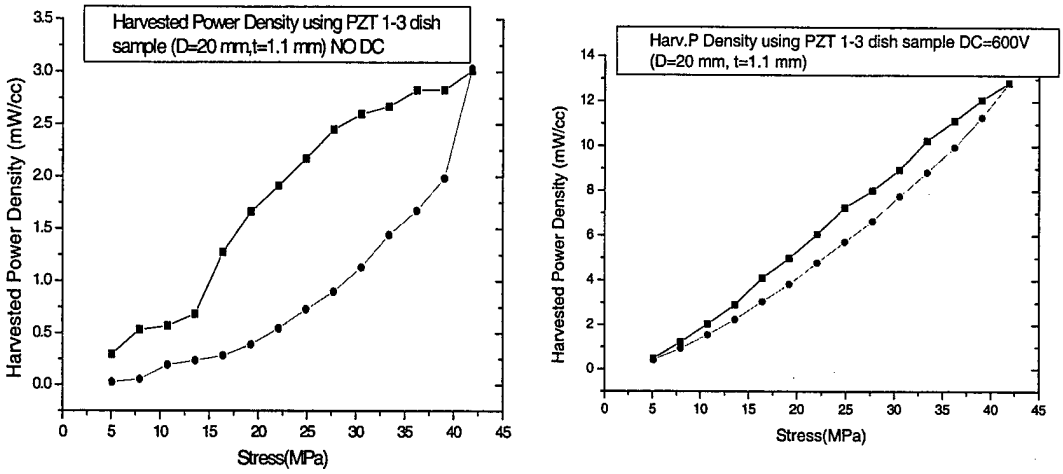


Figure 11. The output electric power density from a 1-3 composite with piezo-ceramic PZT (a) without DC bias field (left) and (b) with a 5.5 kV/cm DC bias field (right). The upper curves are for the increased stress and the lower curves are for the reduced stress during the cycle. Apparently, without DC bias field, the piezocomposite depoled. No depoling occurs under DC bias field and the output power density is higher.

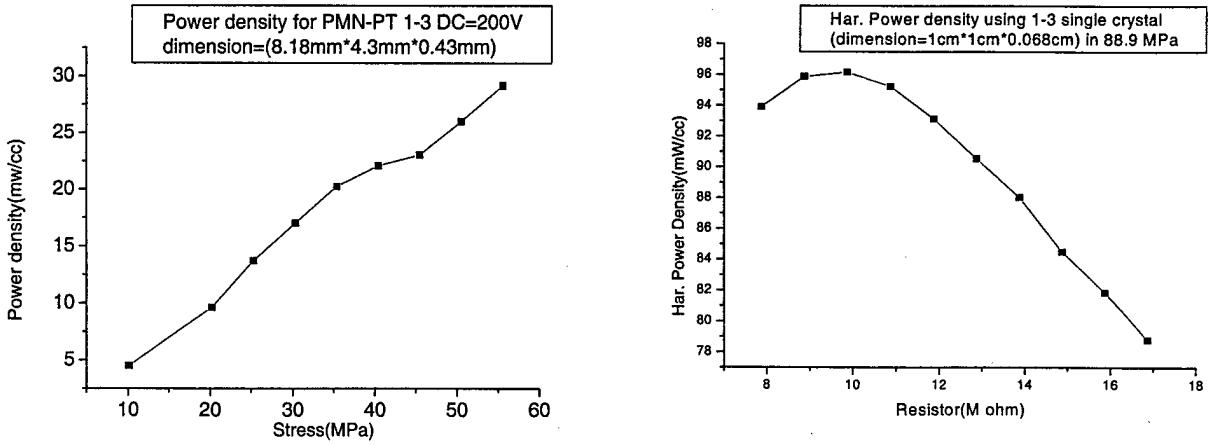


Figure 12. The output electric power density from the1-3 composite with ferroelectric relaxor PMN-PT single crystals (a) as a function of the applied stress signal (left, for the composite with 37% crystals) and under 4.6 kV/cm DC bias and (b) under a stress of 88.9 MPa as a function of the load resistor (right). The maximum output power density reaches 96 mW/cc at 10 MΩ load. The operation frequency is 4 Hz.

Figure 12 presents the experimental data for the 1-3 composites with ferroelectric relaxor single crystal PMN-PT. Figure 12(a) is for the 1-3 composite with 37% of single crystal. In the experiment, a DC bias of 4.6 kV/cm was applied to stabilize the polarization. Figure 12(b) shows how the output power density varies with the load resistor under a stress cycle with T_{max}=89 MPa, here the 1-3 composite contains 56% of PMN-PT single crystals. The output power density can reach 96 mW/cc (at 4 Hz) when the resistor load is optimized. Table III summarizes these experimental results.

As shown from figures 11 and 12, the 1-3 composites with piezo-single crystal can generate two times output power density and show an efficiency more than 2 times higher in comparison with that obtained from 1-3 composites with piezo-PZT ceramics. The results are consistent with the fact that the efficiency of 1-3 single crystal composites is twice of that of 1-3 piezoceramic composites.

No further experiments were conducted related to the power output with other power electronic circuits, for example, the open circuit electric boundary condition, to maximize the system efficiency as discussed in (i).

References:

[1]. Yiming Liu, Kailiang Ren, Heath F. Hofmann and Qiming Zhang, "Investigation of Electrostrictive Polymer for Energy Harvesting," submitted to IEEE Trans. UFFC.
[2]. Ron Pelrine, "Dielectric Elastomers: Generator Mode Fundamentals and Applications," *Proceeding of SPIE, Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices,* vol. 4329, 2001

IV. Summary

The results from this preliminary investigation show that there is a great potential in utilizing the newly developed electroactive materials for the electric energy harvesting during walking as well as from other mechanical sources. Furthermore, by working with smart electronics to tune the material parameters during the energy harvesting cycle, one can achieve much higher energy efficiency in comparison with the electroactive material itself.